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THESIS

RIP CHANNEL MIGRATION IN THE NEARSHORE

by

Courtney M. Minetree

September 2006

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13. ABSTRACT

Video imaging data generated from the Naval Postgraduate School Imaging System (NAPSIS) during November 2004 to June 2006 was analyzed to determine the location of rip channels and track their morphology. During the study period, the rip fields constantly changed in shape, size, and location. Rip channels were found to have a mean migration southward at a rate of 0.16 meters per day with a standard deviation of 7.6 meters per day and maximum rates varying between approximately 30 meters per day north and 30 meters per day south. The migration exhibited a strong seasonal variation with southerly shifts in the fall and winter months, northerly shifts in the late winter and early spring months, and no significant shift in the late spring and summer months.

Directional wave spectra measured every hour at the offshore NOAA buoy were refracted to the 10 meter depth contour at Marina and Sand City and compared with measured spectra at these locations. The significant wave heights at both locations exhibited a correlation of 0.94. Mean wave directions for Marina and Sand City were found to have correlations of 0.83 and 0.34, respectively. These refracted data were then used to calculate sediment transport rates at Stillwell Hall, Fort Ord. Rip channel migration and calculated sediment transport rates were correlated at 0.8, qualitatively confirming the hypothesis that the migration rate of rip channels is a function of modeled alongshore sediment transport.

The sometimes rapid migration of these large scale morphological features is critical to the successful planning and execution of U.S. Navy and Marine Corps beach assaults and the operation of mine warfare. Because amphibious and special forces operate mainly in shallow areas, the modeling of rip current direction and magnitude contributes greatly to effective mission organization and accomplishment. In addition to causing mines to drift, rip currents transport sediment that can cause the underlying morphology to change, possibly covering bottom mines and creating a potential hazard for military forces operating in the area. Being able to predict where mines may be drifting and how much sediment has concealed them is a necessity in securing a littoral battlespace.

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RIP CHANNEL MIGRATION IN THE NEARSHORE

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I. INTRODUCTION

A. BACKGROUND

1. Rip Currents

Rip currents are strong, shore-normal, seaward-directed jets that develop in narrow channels within the surf zone (MacMahan *et al.*, 2005). Because rip currents can flow to 3 meters per second, the study of their behavior is important in understanding the transport of sediment and pollution offshore and alongshore, beach erosion and accretion, and variations in coastal morphology (Holt, 2003). Rip currents also significantly impact the recreational swimmer, accounting for more than 80% of lifeguard rescues. For example, in the state of Florida, it has been reported that more people lose their lives to rip currents than to any other natural hazard, including tornadoes, hurricanes, and lightning (Bogle *et al.*, 2001).

Rip currents are formed from variations in the wave set-up pattern alongshore, which effects the coastal circulation. Smaller onshore directed jets or feeder currents in shoals cause the neighboring water surrounding the rip to converge into the main rip channel. Once in the main rip channel, the flow is then directed offshore and dispersed out to sea (MacMahan *et al*., 2005, Bogle *et al*., 2001).

Most models and experiments dealing with rip current formation and behavior have been coupled to their underlying morphology. Past attempts to relate rip morphology to local wave climate, sediment size, and shoreline orientation have resulted in poor to fair correlation (Woods, 2005). In recent years, the accuracy in identifying rip currents, tracking their movement, and calculating their spacing and shape has greatly improved due to the use of video imaging techniques. The risk of instrument vandalism or damage is greatly reduced because video cameras are placed out of normal reach and away from the turbulent surf zone. Video imaging is also able to survey a larger area over a continuous time range, thereby, increasing the spatial and temporal depth of information gathered (Bogle *et al*., 2001). The succession of deeper rip channels and feeder shoals along the coast are quite evident in video images. Similar when viewed by

the naked eye, rip channels are seen in video images as deeper, darker features normal to the coast, while the shallower, white foamy areas are associated with the feeder channels (Holman *et al*., 2006).

2. Military Impact

A thorough understanding of rip currents and their migration is critical to the successful planning and execution of U.S. Navy and Marine Corps beach assaults and the operation of mine warfare. Because amphibious and special forces operate mainly in shallow areas, the modeling of rip current direction and magnitude contributes greatly to effective mission organization and accomplishment. In addition to causing mines to drift, rip currents transport sediment that can cause the underlying morphology to change, possibly covering bottom mines and creating a potential hazard for military forces operating in the area. Being able to predict where mines may be drifting and how much sediment has concealed them is a necessity in securing a littoral battlespace.

B. STUDY SITE

Monterey Bay, located approximately 200 km south of San Francisco, is a roughly semi-circular embayment on Central California's coast, bordered by Santa Cruz in the north and Monterey in the south. The 48 km of shoreline surrounding Monterey Bay is located in a microtidal, swell-dominated environment (Woods, 2005). The specific focus area for this study is the shoreline at Fort Ord, located in the center of the southern portion of the bay (Figure 1). Because Monterey Bay is sheltered by headlands to the North and South, the Northwest Pacific swell entering the bay forms a narrow direction wave train. As the wave train passes over the Monterey Canyon, the waves are strongly refracted and approach the shoreline at a near normal incidence angle. This refraction forms a significant gradient of wave energy from the sheltered, barred beach of Del Monte to the energetic, rip-dominated shore of Marina State Beach (Holt, 2003). Rip currents are observed in the study area continuously throughout the year. The nearshore morphology of the southern Monterey Bay is characterized by a transverse bar and rip system. The foreshore is relatively steep with a slope of about 1:10. The shoreline is characterized by mega-cusps at the same alongshore scale of O(200m) as the rip current. The embayment of the mega-cusps is centered on the rip. Higher on the beach are the

typical O(35m) wide beach cusps. The beach face flattens out to a low-tide terrace (1:100), decreasing further offshore to a slope of about 1:20 (MacMahan *et al*., 2004).

C. OBJECTIVES

The objective of this thesis is to determine the migration rates of the rip currents at Stillwell Hall, Fort Ord. It is hypothesized that the migration rate of these rip channels is a function of alongshore sediment transport rate.

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II. DATA

A. VIDEO IMAGING

Video image data are generated from four camera sites as part of the Naval Postgraduate School Nearshore Imaging System (NAPSIS). The NAPSIS generates three different types of images: 1) a snapshot image, 2) a time exposure image, and 3) a pixel variance image. Of the four sites, Stillwell Hall is in the most ideal location to observe rip channels due to the high camera elevation and well-developed rip activity within the coverage area, and is the data analyzed in this thesis. Two cameras were located atop a 7 meter tower on a 35 meter dune at Fort Ord, with good coverage approximately one kilometer to the north and south. The cross-shore coverage area was approximately 400 meters wide.

During each daylight hour (0700 to 1800 PST), a 20 minute time-exposure image was acquired (Figure 2, top panel). Time-exposure images are the most useful in the studying of the nearshore region as they average conditions over a long exposure time and are mathematically averaged to remove statistical uncertainties and fluctuations due to incident wave modulations (Lippmann and Holman, 1989). In order to quantify the information, the images are rectified into plan view coordinates. Ground Control Points (GCPs) are used to ascertain the positioning of the objects between the 2-D image and 3-D world coordinates assuming the waves are at mean sea level (Holland *et al*., 1997). The GCPs used at Stillwell Hall, Fort Ord, are circular targets 0.3-1 meter in diameter, depending on the distance from the cameras, and were surveyed using Kinematic GPS with an accuracy of O(1cm). This rectification process allows the image to be portrayed in a plan view with the camera as the origin, and the alongshore beach in X and Y coordinates. Holland et al. (1997) computed the error between world and image coordinates to be O(1m) for the rectified images. This same order of error was computed by Holt (2003) for NAPSIS. The rectified images were then averaged over the entire day to create a “daytimex” image (Figure 2, bottom panel) (Woods, 2005).

The bathymetry of the study site can be inferred from the wave breaking patterns in the images. Waves break when they reach shallow water creating foam that is displayed as white in the video images (Thornton and Guza, 1983). Non-breaking waves

are displayed as darker regions in the images, corresponding to deeper depths (Lippmann and Holman, 1989). Rip channels are interpreted to be located in the darker (deeper) portions of the images, extending in the cross-shore direction between the areas of breaking waves on the shoals (lighter) (Figure 2, bottom panel) (Lippmann and Holman, 1989, van Enckevort and Ruessink, 2001, Holman *et al.*, 2006).

B. RIP LOCATIONS

Rip current locations were determined from video images from November 1, 2004, through June 30, 2006. To aid in choosing rip channel locations, three alongshore pixel intensity lines were overlaid on each video image. The three pixel lines are separated by 20 meters in the cross-shore direction, starting at 150 meters from the shoreline and spanning to 210 meters (Figure 3). Pixel intensity is calculated every meter in the alongshore direction. The pixel intensity lines are especially useful when viewing images taken during inclement weather or high wave conditions when intensity variations between rip channels and shoals are less distinct. During poor weather, the entire surf zone is restricted in visibility due to rain or fog. In high wave conditions, the surf zone is visible, but the underlying features are unclear due to intense breaking over the entire bar. Although the channel locations may be visually indiscernible in these images, the plotted pixel lines still depict changes in intensity. The rip channel is chosen at the location of minimum intensity (Figure 3). Locations of rip channels chosen daily along the shoreline as a function of time are shown in Figure 4 (top panel).

C. WAVE CLIMATE

Deep water hourly observed wave statistics of wave height (H_s), peak period (T_p), and mean wave direction (D_p), were acquired from the NOAA directional wave buoy, Number 46042, located approximately 27 NM west of Monterey Bay (Figure 5) for the period December 2003 through June 2006. Also shown are wave data from an ADCP located at a water depth of 12 meters off Sand City for the beginning of 2004. The wave heights inside the bay are generally smaller than offshore due to sheltering by the headlands of the bay.

From October to May, the most dominant wave patterns affecting the Monterey Bay originate from storms in the western Pacific up to the Aleutians. As the westerly to northwesterly wave trains enter the Bay, they are refracted to a near-normal incident

angle as they approach the shore. During the summer months (June to September), a persistent high pressure system results in strong northwesterly winds and seas. At the same time, the South Hemisphere Swell is most prominent, producing a small background wave climate from the south. The southern areas along the Monterey Bay coast are not significantly affected by this southerly swell due to protection of the Monterey Peninsula. Regional low pressure systems can also cause variations in the local swell (Stamski, 2005). The significant wave heights are noticeably higher and wave periods noticeably longer during the winter months (December to March) than in the summer months (Xu, 1999) (Figure 5).

D. COMPARISON WITH REFRACTION MODEL

An objective is to calculate sediment transport at the Fort Ord site. However, wave data are not available at this site. Wave data refracted to the site throughout Monterey Bay from the offshore NOAA buoy are available from the California Data Information Program (CDIP) (see for example, Figure 6). To insure confidence in the refraction model, measured data at two shallow water sites are compared with the refracted wave heights and mean directions. Directional wave spectra were measured with two Datawell Directional Waverider buoys situated at a depth of 17 meters and located in Marina and Sand City from May 1, 2002, to July 7, 2002, (yeardays 120-188). These data are used to verify the wave spectra refracted from the offshore wave buoy. The significant wave height and mean wave direction are compared. Significant wave heights for the buoy data were calculated using

$$H_s = 4\sqrt{\int_{-\pi/2}^{\pi/2}\int_{.04Hz}^{.25Hz} S(f,\alpha)\,d\alpha\,df}$$

where $S(f,\alpha)$ represents the directional energy spectra values over the sea-swell frequency (f) band 0.04-0.25 Hz and direction (α) +/- 90 degrees of shore normal. Directional wave spectra data were measured at offshore NOAA Buoy 46042 and refracted to the 10 meter depth contour at Marina and Sand City (provided by Bill O'Reilly) (Figure 7, top panel).

A comparison of significant wave heights for the modeled refraction and Waverider buoy data show good correlation for both Marina and Sand City sites. A previous comparison of these data sets was conducted by Holt (2003), displaying an

under-prediction by the model for significant wave height by approximately 60% at Marina and 50% at Sand City. Based on this analysis, the refraction model was expanded to include waves passing over the shelf from the Farallon Islands to Santa Cruz (O'Reilly, 2006). The wave heights at the nearshore buoy often exhibited enhanced values during times of sea breeze that were not seen in the waves refracted from the offshore buoy (Figure 7, bottom panel). In the comparisons, both data sets were resampled to delete the times of sea breezes, so that only the measurements acquired between the hours of 0000 and 1200 (PST) for each yearday were included in the comparison (see for example, Figure 8). It was further found that the best correlation between the modeled and measured significant wave heights was for a frequency bandwidth of 0.04-0.25 Hz. Using this bandwidth improved the correlation by approximately 10% compared with using a broader bandwidth. The resulting correlations were 0.94 for significant wave heights at both Marina and Sand City (Figure 8).

For both the modeled and buoy data, the mean wave direction values were weighted by their corresponding energy spectral values. A comparison of mean wave direction at the energy peak of the spectrum for the modeled refraction and Waverider buoy data at Marina and Sand City show fair correlation for Marina and poor correlation for Sand City. With the entire frequency range included and the hours unfiltered, the correlation was 0.48 at Marina and 0.03 at Sand City. To improve the correlation, the hours were selected to exclude sea breeze and the frequency range was varied for each study site individually. At Marina, the frequency range of 0.06-0.11 Hz resulted in the best possible correlation of 0.83 (Figure 9, top panel) suggesting higher frequency waves were present at one site and not the other. At Sand City, the frequency range of 0.1-0.25 Hz resulted in the best possible correlation of .34 (Figure 9, bottom panel). The poorer correlation at Sand City is most probably due to its sheltered location in the lee of the Point Pinõs headland requiring severe wave refraction to reach the shallow water location. The Marina data is more representative of the Fort Ord site.

E. ALONGSHORE SEDIMENT TRANSPORT

Given the good correlation between the modeled and measured significant wave heights and mean wave directions at Marina, modeled refracted data can be substituted for raw buoy data when calculating nearshore predictions at Fort Ord with some

confidence. It is hypothesized that the migration rate of rip channels is a function of alongshore sediment transport, Q_s, given by (U.S. Army Corps of Engineers, 1996).

$$Q_s = KS_{yx}C_b$$

where dimensional coefficient, K=1290 m^3-s/N-yr, S_{yx} is the radiation stress, and C_b is the phase speed at wave breaking. Assuming straight and parallel contours offshore, the radiation stress is conserved up to breaking and, therefore, can be measured anywhere outside the surf zone. Calculating the S_{yx} from the 10 meter refracted waves using

$$S_{yx} = E\frac{C_g}{C}\sin\overline{\alpha}\cos\overline{\alpha}$$

where energy, E,

$$E = \frac{1}{16}\rho g H_s^{\ 2}$$

the ratio of group velocity to phase speeds, $\frac{C_g}{C}$,

$$\frac{C_g}{C} = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right]$$

and $\overline{\alpha}$ is the mean wave angle at the peak wave frequency calculated using measured Fourier directional coefficients (a_1, b_1)

$$\overline{\alpha} = \tan^{-1}\left(\frac{b_1}{a_1}\right).$$

The phase speed at breaking (C_b) is calculated assuming shallow water waves

$$C_b = \sqrt{gh_b}$$

where h_b is the water depth at breaking. The water depth at breaking is related to the wave height at breaking (H_b) by (Thornton and Guza, 1983)

$$h_b = \frac{H_b}{\gamma}$$

where $\gamma = 0.6$ when using significant wave heights. For these calculations, it is assumed H_b is approximately equal to the H_s calculated from the refracted waves in 10 meter water depth. A comparison of migration rates and alongshore sediment transport is discussed in the next section.

III. RESULTS

A. RIP CHANNEL SPACING

During the study period, the rip fields constantly changed in shape, size, and location at Stillwell Hall. In the winter months, the rip channels were observed more often. During this timeframe, the rip channels appeared to merge and coalesce, resulting in fewer rip channels in the spring and summer months. Rip spacing statistics were determined by calculating the differences in alongshore location between adjacent rip channels for all yeardays in which rips occurred or could be measured (Holman *et al*., 2006). Rip spacing was measured qualitatively and found to be approximately 150 meters in the winter months, increasing to approximately 250 meters in the summer months.

Generally, rip current spacing is driven by beach state (Bogle *et al*., 2001). As described in Wright and Short (1984) and Bogle *et al.* (2001), the change in rip spacing coincides with the transitioning of beach states. From November 2004 to late January/early February 2005, the morphology of the nearshore region at Stillwell Hall exhibited the characteristics of a transverse bar and rip state (Figure 10, top panel). The morphology of this state is characterized by several bars that are perpendicular to the shore and attached to the beach, which, consequently, segregate the individual rip circulation systems (Short, 1999). In early February 2005, the transverse bar and rip state transitioned into a longshore bar-trough state and maintained this formation until the beginning/middle of September 2005 (Figure 10, bottom panel). The longshore bar-trough state is characterized by a near-continuous longshore bar located approximately 100 to 150 meters off the coast, separated by a trough approximately 50 to 100 meters wide and 2 to 3 meters deep. The longshore bar is crossed by rip currents spaced further apart than those observed during the transverse bar and rip state (Short, 1999). At the beginning/middle of September 2005, the beach again developed into a transverse bar and rip state. At the beginning of January 2006, the morphology of the nearshore region once again transitioned into a longshore bar-trough state. The beach state during some time periods is difficult to discern due to discontinuities in the data. These discontinuities

result from not being able to identify rip channels in the video images during periods of inclement weather, high wave activity, or camera malfunctions. Days with missing data are evident by the gaps in the rip channel locations.

B. RIP CHANNEL MIGRATION

Periods of southerly rip channel migration were observed from November 1, 2004, to approximately December 20, 2004, and from April 1, 2005, to approximately December 20, 2005. Weak or even northward movement was observed from approximately December 21, 2004, to March 31, 2005, and from approximately December 21, 2005, to June 30, 2006 (Figure 4, top panel).

Migration rates and directions were determined from the calculated slope of three adjacent rip current location points. The calculations were completed for selected time periods for one rip channel at a time when data were contiguous, owing to the many discontinuities in the data. From a chosen start location, the slope was calculated using three contiguous location points starting with the prior point to the point directly after the beginning location. The slope at each successive point was then calculated until the end point was reached. This process was continued for all rip current locations throughout the study period. The migration rates (slopes) were then averaged for each day (Figure 4, bottom panel). Noticeable southerly shifts are evident in the fall and early winter months. Noticeable northerly shifts are evident in the late winter and early spring months. Migration rates and directions do not significantly change in the late spring and summer months. Histograms of migration rates in the fall and early winter months of 2004 and late winter and early spring months of 2005 are shown in Figure 11. The mean migration shifted from a southward rate of 1.72 meters per day in the fall and early winter months to a northward rate of 1.65 meters per day in the late winter and early spring months. A histogram of all migration rates is shown in Figure 12. The mean migration was southward at a rate of 0.16 meters per day with a standard deviation of 7.6 meters per day and maximum rates varied approximately 30 meters per day both north and south.

The alongshore sediment transport rate (Q_s) at Stillwell Hall, Fort Ord, was calculated from the significant wave height, period, and directional Fourier coefficient values supplied by Bill O'Reilly (Figure 13). The shore normal angle was manually measured from a chart of the Monterey Bay and subtracted from the mean direction

values, $\overline{\alpha}$, to ensure the values were considered approaching the beach at shore normal. Northerly transports are evident in the winter and early spring months. Southerly transports are evident in the late spring to fall months. Linear regression was performed, comparing the alongshore sediment transport and mean migration rates (Figure 14). Using the original measured angle from the chart, the resulting correlation is 0.41.

The mean migration for each yearday was calculated by integrating the measured mean migration rates (i.e. summing each yearday's average migration rate) multiplied by the uniform time step of one day (Figure 15, bottom panel). The net sediment transport was calculated in a similar manner by integrating the calculated sediment transport rates (Figure 15, top panel). Approximate southerly shifts occurred in the fall and early winter months of 2004 and 2005, respectively, for both mean migration and net alongshore sediment transport. Similarly, rip channel migration shifted to a northerly direction in the early spring months of 2005 for both calculations. However, a northerly shift was not evident in the early spring months of 2006 for mean migration but was apparent in the net alongshore sediment transport. Additionally, the net sediment transport during the summer and early fall of 2005 and summer of 2006 exhibit a steady increase. The mean migration, however, during these same time periods, maintains a relatively consistent behavior. Linear regression comparing the mean migration and net alongshore sediment transport using the original measured angle from the chart results in a correlation of .42 (Figure 16).

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IV. DISCUSSION

Owing to the sensitivity of the sediment transport to wave angle and in the inaccuracies of visually choosing a shore normal from a chart (accuracy approximately +/- 1 degree), an optimal shore normal was determined by rotating $\overline{\alpha}$ to obtain maximum correlation between mean migration and net sediment transport. By rotating the angle 0.9 degrees south, the correlation between mean migration rate and alongshore sediment transport rate improves from 0.41 to 0.43 (Figure 17). By applying this optimized angle, the linear regression between mean migration and net alongshore sediment transport improves from 0.42 to 0.81 (Figure 18). A strong seasonal cycle is apparent in the regression plot with Qs over predicting migration to the north in the summer months and underpredicting it in the winter.

The trend of the rip channels to move south in the late fall and early winter months, north in the late winter and early spring months, and stay neutral in the late spring and summer months suggests a seasonal pattern in the rip current migration. This pattern is qualitatively observed in the rip location plot (Figure 4, top panel). The behavior of the mean migration and net alongshore sediment transport over the study period further support the seasonal trend of rip channel movement (Figure 15).

The net alongshore sediment transport steadily increases during the summer months of 2005 and 2006. Mean migration during these time periods, however, stays relatively constant. It is hypothesized that sea breezes caused by inshore wind fields in the coastal Monterey Bay area, acting as an opposing force, are most likely causing the mean migration to stay relatively stationary during the summer months. The modeled data, however, is not affected by these inshore wind fields because it is generated from the NOAA offshore buoy. As a result, the calculated net alongshore sediment transport overpredicted migration during the summer.

Comparing time series of the net sediment transport and migration of rip channels (Figure 15), it appears the migration lags the sediment transport. The cross-correlation between mean migration and net alongshore sediment transport was calculated to quantitatively measure the phase lag (Figure 19). The maximum correlation is 0.83 at a

10 day lag between mean migration and the net alongshore sediment transport. The correlation has another maximum at approximately 365 days after the maximum peak, indicating an annual cycle in the mean migration and net alongshore sediment transport.

V. CONCLUSIONS

The migration rates of rip channels at Stillwell Hall, Fort Ord, in the Southern Monterey Bay were studied from November 1, 2004, through June 30, 2006. Video imaging allows an accurate long-term calculation of rip channel locations. The shading in the daytimex images aided in discerning the bathymetry and wave breaking patterns of the nearshore environment at the study site. Despite the technological advances associated with video imaging, the process still allows for subjectivity when discerning rip channel locations. The pixel intensity lines overlaying the rectified images were particularly useful during inclement weather.

From the rip location plot, the spacing between successive channels was qualitatively measured. Similar to the findings of Woods (2005), rip spacing was determined to be approximately 100 meters in the winter months, increasing to approximately 200 meters in the summer months. A beach state transition was also observed during the study period. During the fall and winter months, the beach exhibited a transverse bar and rip state. In the spring and summer months, the beach transitioned into more of a longshore bar-trough state.

Rip channels were found to have a two year mean migration southward at 0.16 meters per day with a standard deviation of 7.6 meters per day and maximum rates varying between approximately 30 meters per day north and 30 meters per day south. The migration exhibited a strong seasonal variation with southerly shifts in the fall and winter months, northerly shifts in the late winter and early spring months, and no significant shift in the late spring and summer months. This detectable seasonal trend in rip migration is statistically significant, which is evident in the sectional rip location plot and histograms in Figure 11.

The correlation between refracted and buoy measured significant wave heights at Marina and Sand City resulted in a correlation of 0.94. Mean wave directions for Marina and Sand City were found to have correlations of .83 and .34, respectively. The waves at Marina are most similar to Fort Ord (located 5 km south). These refracted data were then used to calculate sediment transport rates at Stillwell Hall, Fort Ord with confidence.

Mean rip channel migration rates and alongshore sediment transport rates were correlated at .43 using the southerly rotated optimized shore normal angle. Annual variations were observed in the mean migration and alongshore sediment transport rates. Northerly transports were evident in winter and early spring months, and southerly transports were evident in the late spring to fall months for alongshore sediment transport rates. Mean migration rates exhibited similar patterns, with the exceptions of a southerly shift in the spring of 2006 and consistent behavior during the summer and early fall of 2005 and summer of 2006.

The sensitivity of alongshore sediment transport to wave angle was demonstrated by the linear regression of mean migration and net sediment transport. Using the hand measured shore normal angle resulted in a correlation of 0.42 between mean migration and net alongshore sediment transport. Optimizing the linear regression coefficients by rotating the shore normal 0.9 degrees to the south, the linear regression between the two was correlated at 0.81, qualitatively confirming the hypothesis that migration rates of rip channels are a function of alongshore sediment transport.

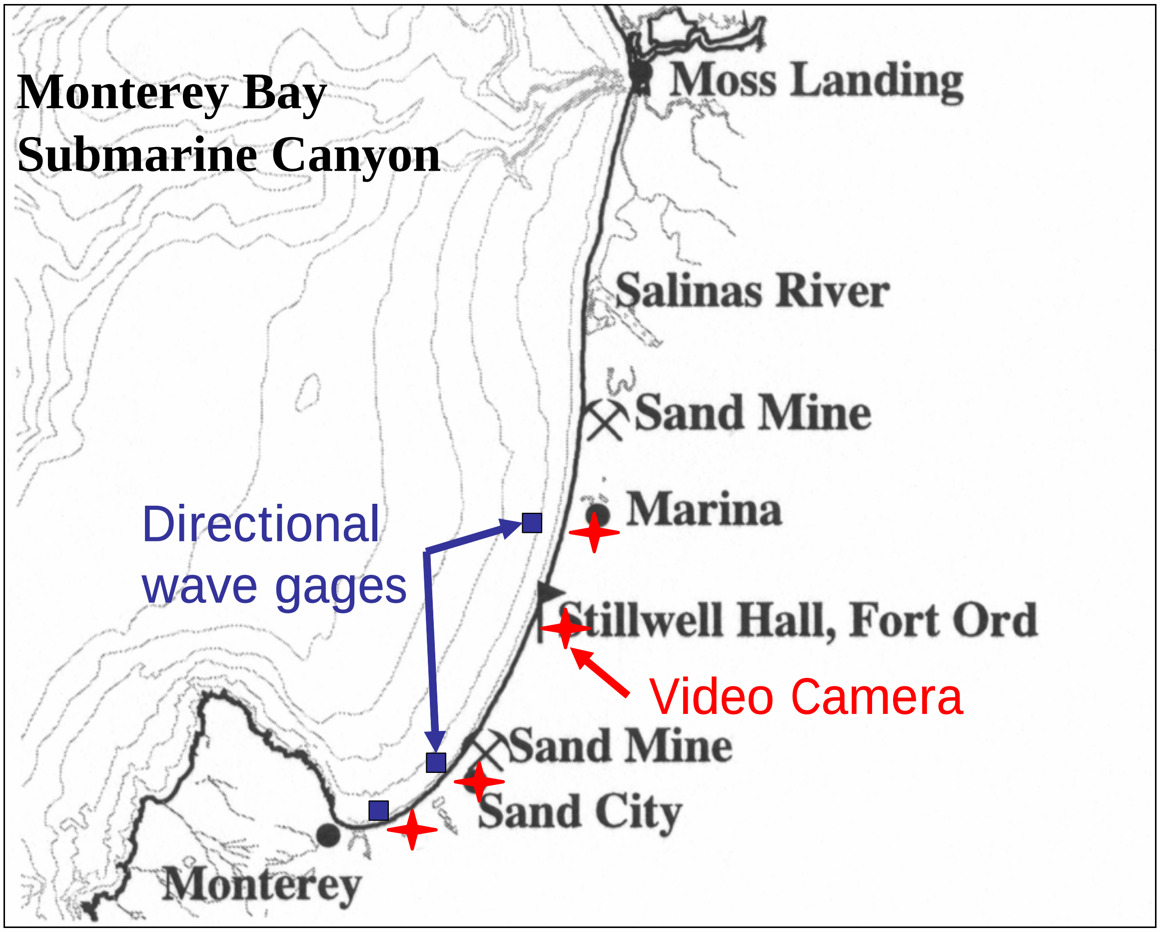

Figure 1. Study area. Directional wave gages are offshore at Marina and Sand City. Video camera used for imaging is at Stillwell Hall, Fort Ord.

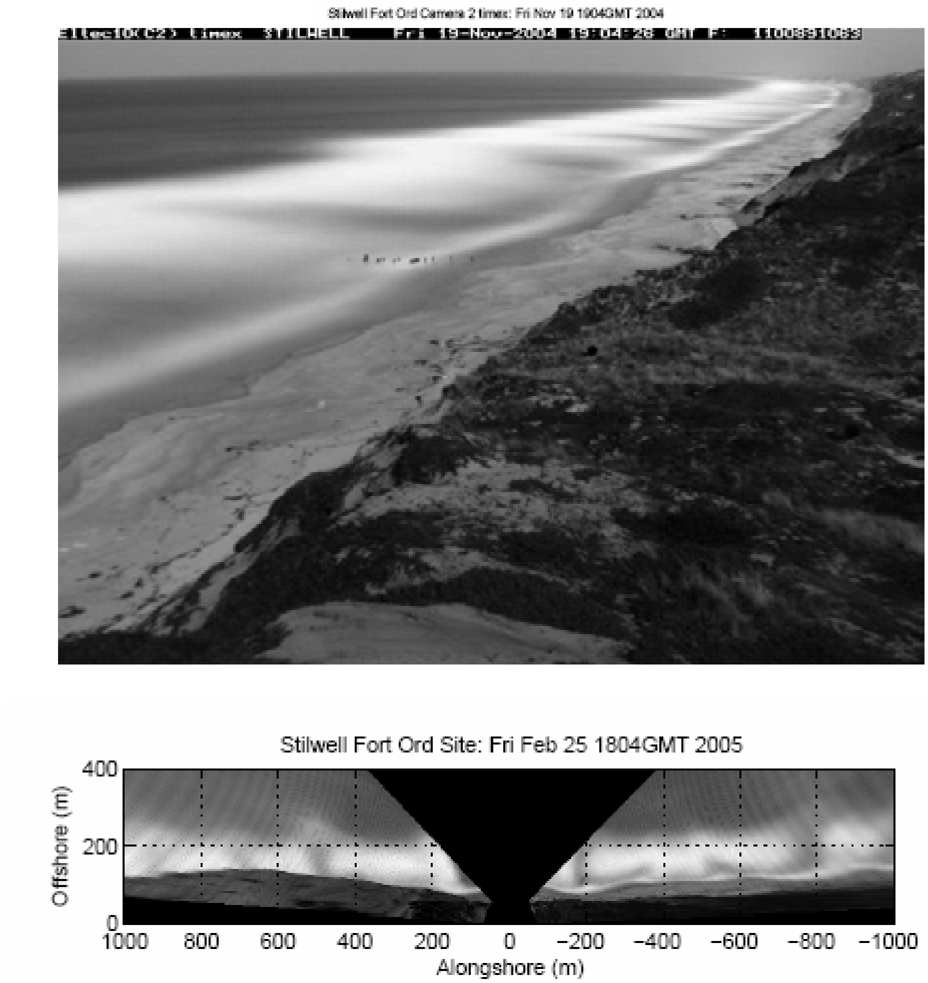

Figure 2. Example of time exposure image taken at Stillwell Hall, Fort Ord, by NAPSIS (top panel). The bottom panel is an example of an image in plan view after rectification. Deeper depths are darker areas (less breaking), and lighter areas are shallower depths (more breaking).

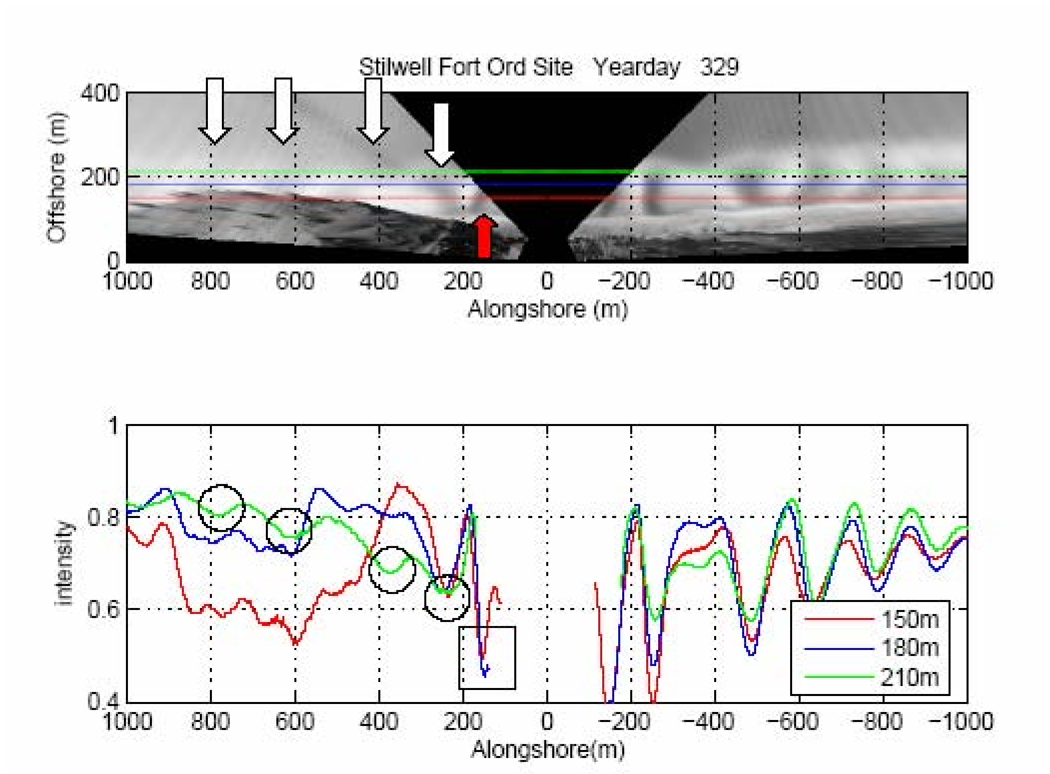

Figure 3. An example of a daytimex image. The pixel intensity lines aid the observer in choosing the correct location of the rip channel. Rip locations are located in areas of lower intensity, annotated by the circles and white arrows. Also illustrated is how the 210 meter intensity line does not detect the rip channel close to the camera's origin, looking south (annotated by the red arrow and box).

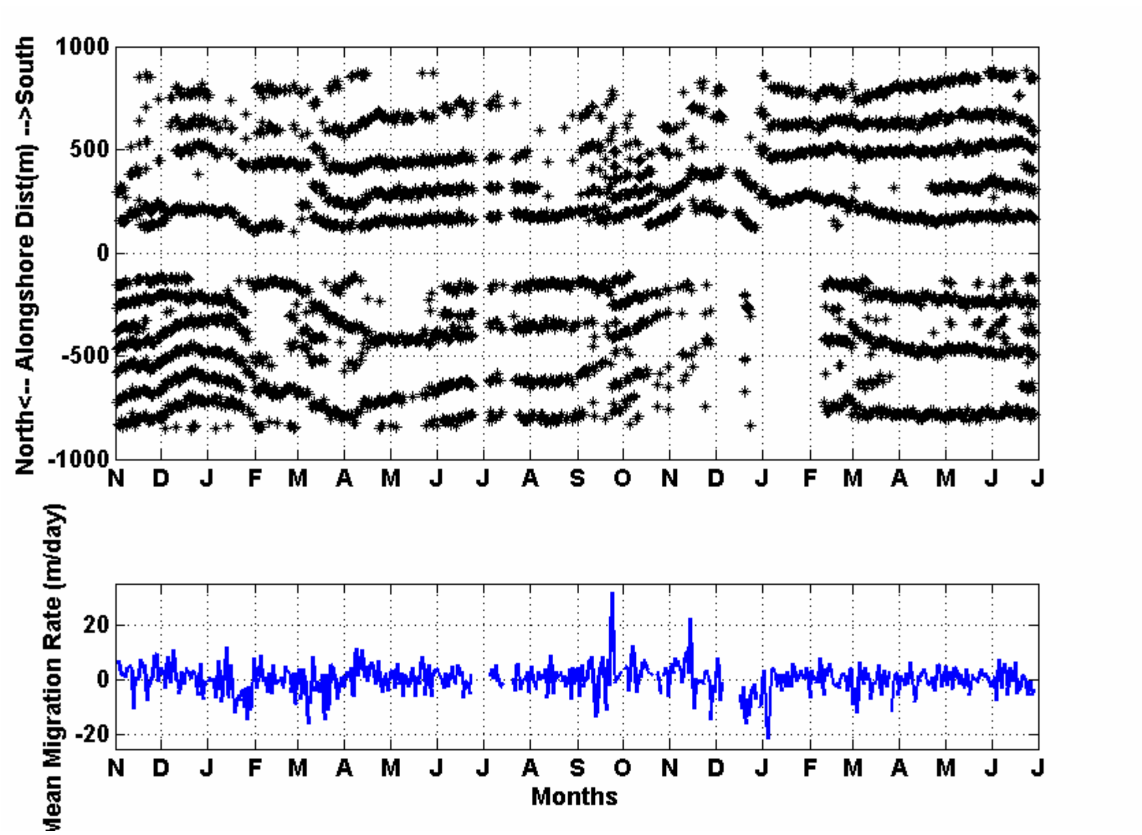

Figure 4. The location of the rip channels at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006 (top panel). The mean migration rate or slope per yearday (bottom panel).

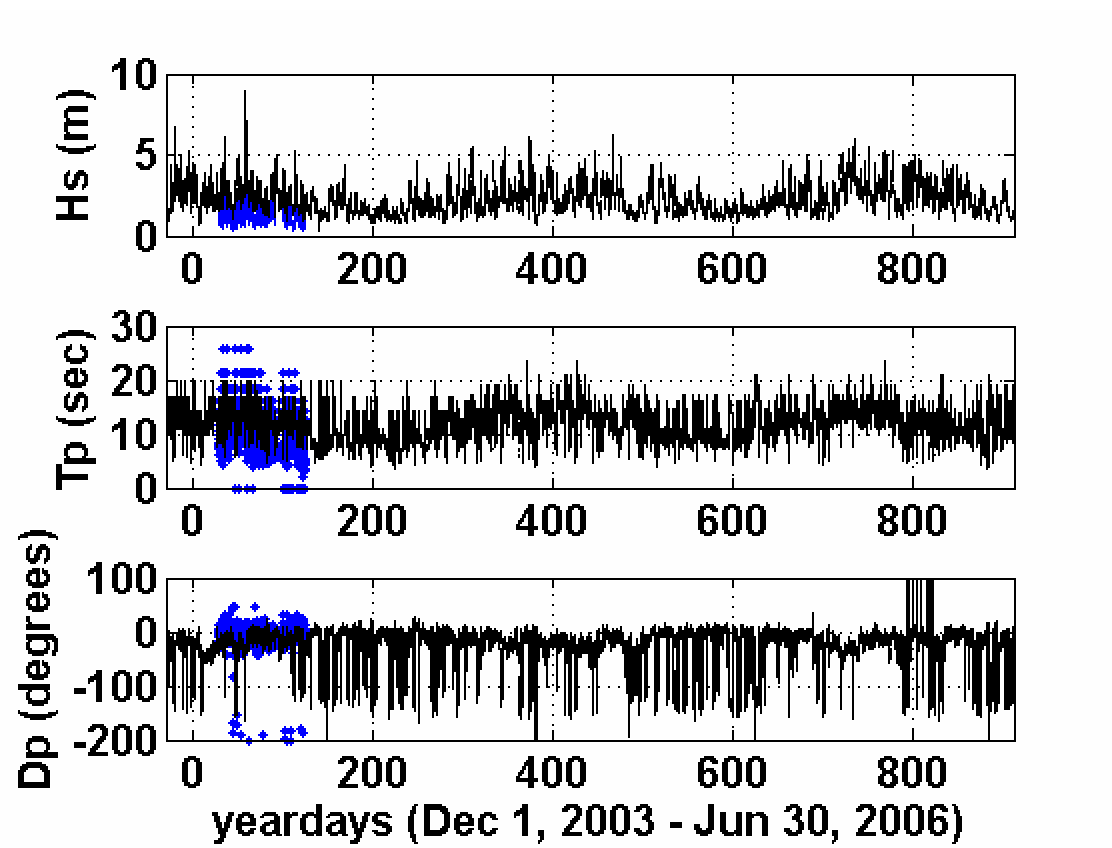

Figure 5. Significant wave heights (top panel), peak wave period (middle panel), and mean wave direction at shore normal (bottom panel) measured from offshore NOAA buoy 46042. The blue dots are ADCP measurements acquired in 12m water depth off of Sand City.

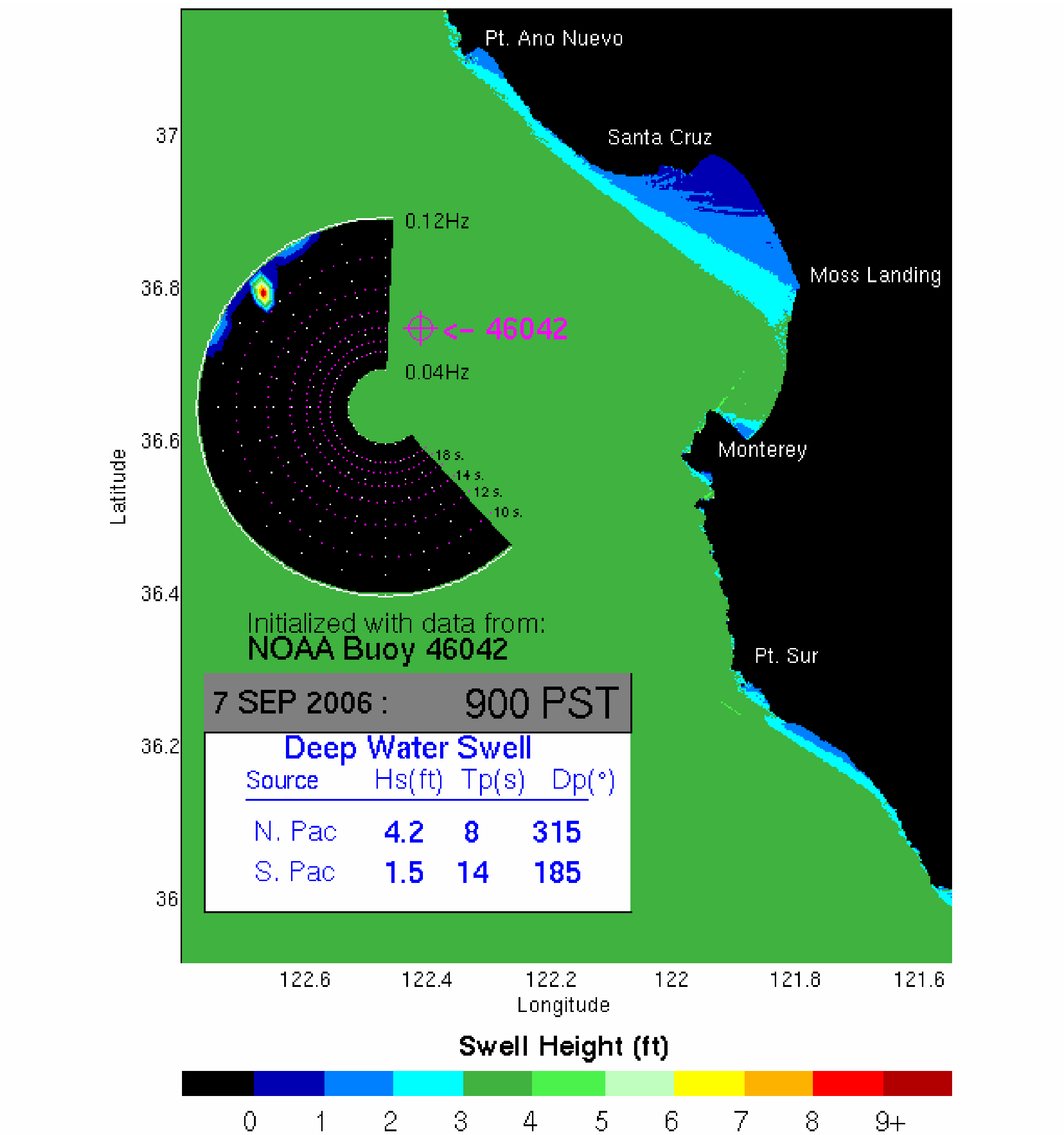

Figure 6. Refraction of directional wave spectrum in deep water measured at NOAA buoy 46042 to Monterey Bay shoreline (O'Reilly, 2006).

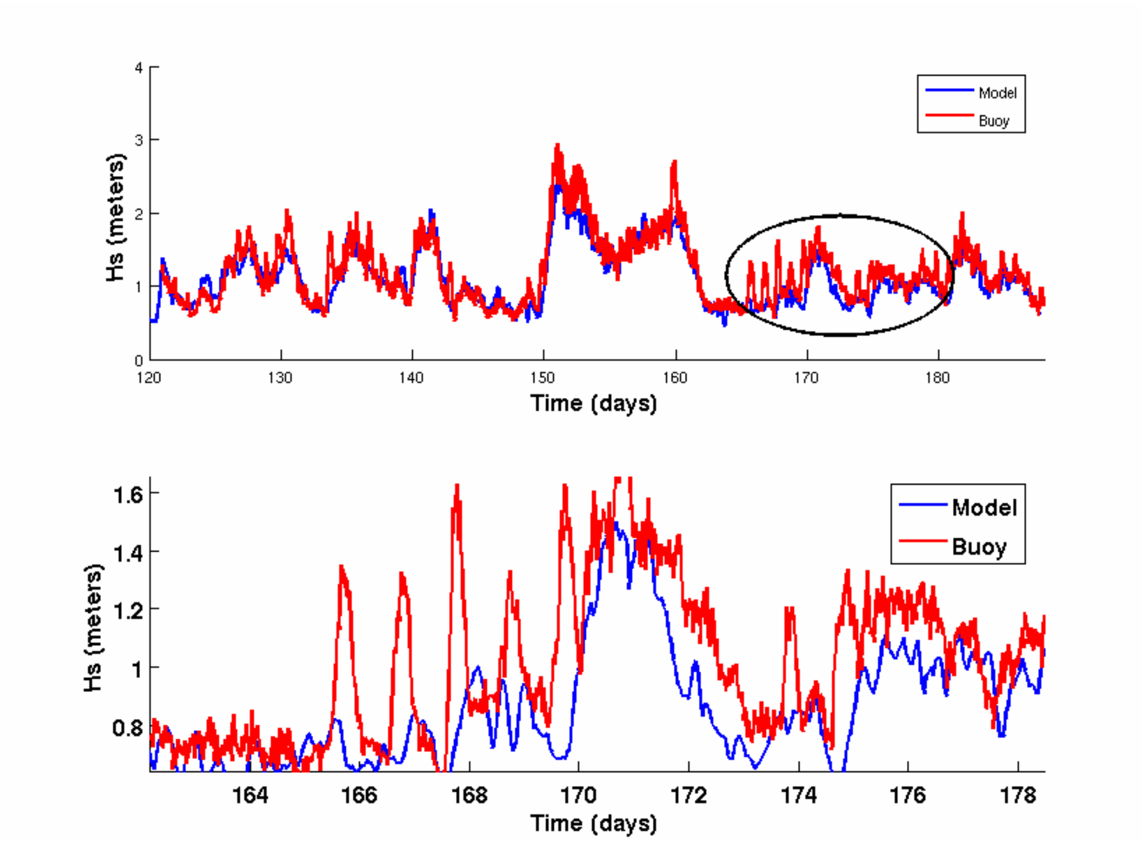

Figure 7. Significant wave height comparison of buoy and refraction model data for Marina from May 1, 2002, to July 7, 2002 (yeardays 120-188) (upper panel). Magnification of specific yeardays at Marina exhibiting the difference in significant wave height values between the O'Reilly refraction model and the buoy measured data (lower panel).

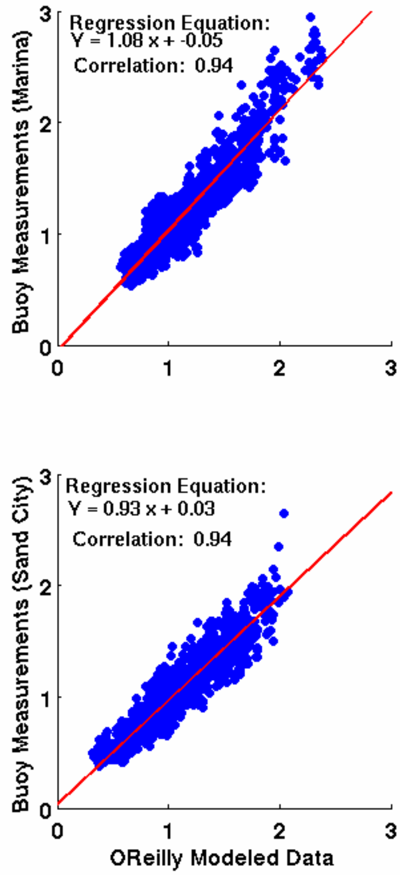

Figure 8. Linear regression of significant wave height for the buoy and refraction model data for Marina and Sand City from May 1, 2002, to July 7, 2002 (yeardays 120-188).

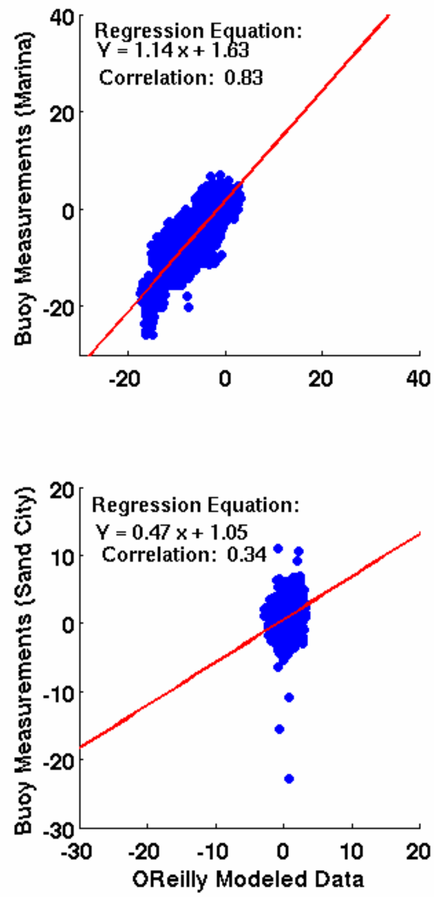

Figure 9. Linear regression of mean wave direction for the buoy and refraction model data for Marina and Sand City from May 1, 2002, to July 7, 2002 (yeardays 120-188). At Marina, mean wave direction was measured over the frequency range 0.06-0.11 Hz. At Sand City, mean wave direction was measured over the frequency range 0.1-0.25 Hz.

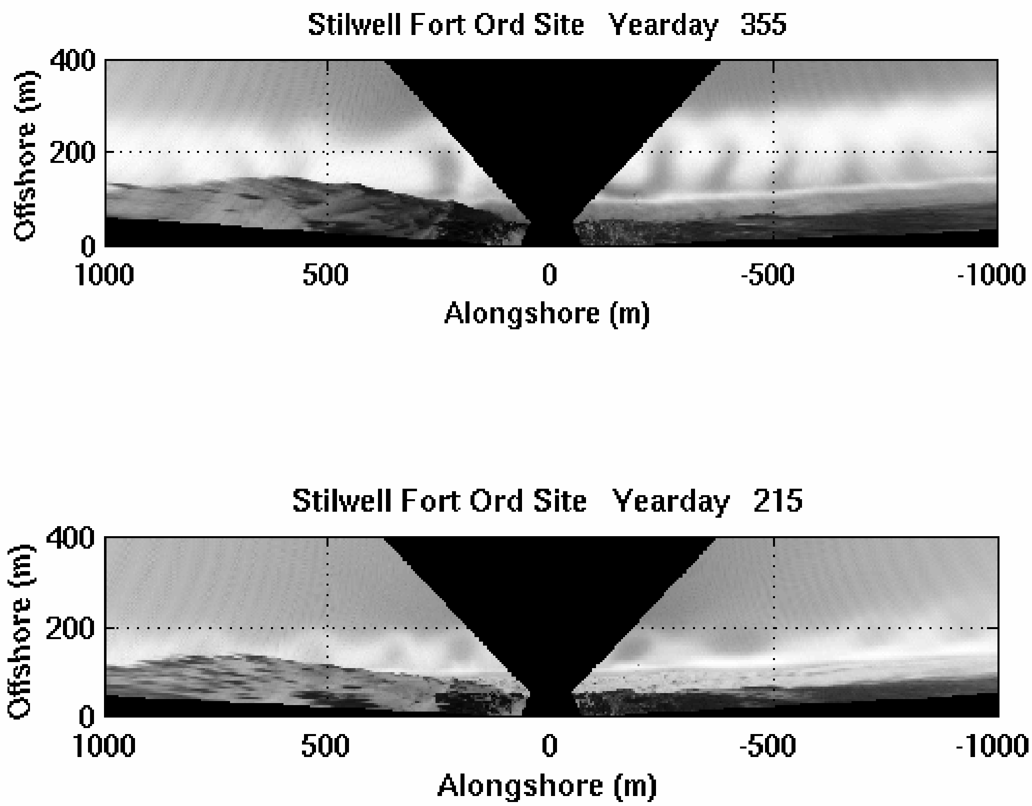

Figure 10. Yearday in December 2004 showing the formation of a transverse bar and rip state (top panel). Yearday in June 2005 showing the formation of a longshore bar-trough state (bottom panel).

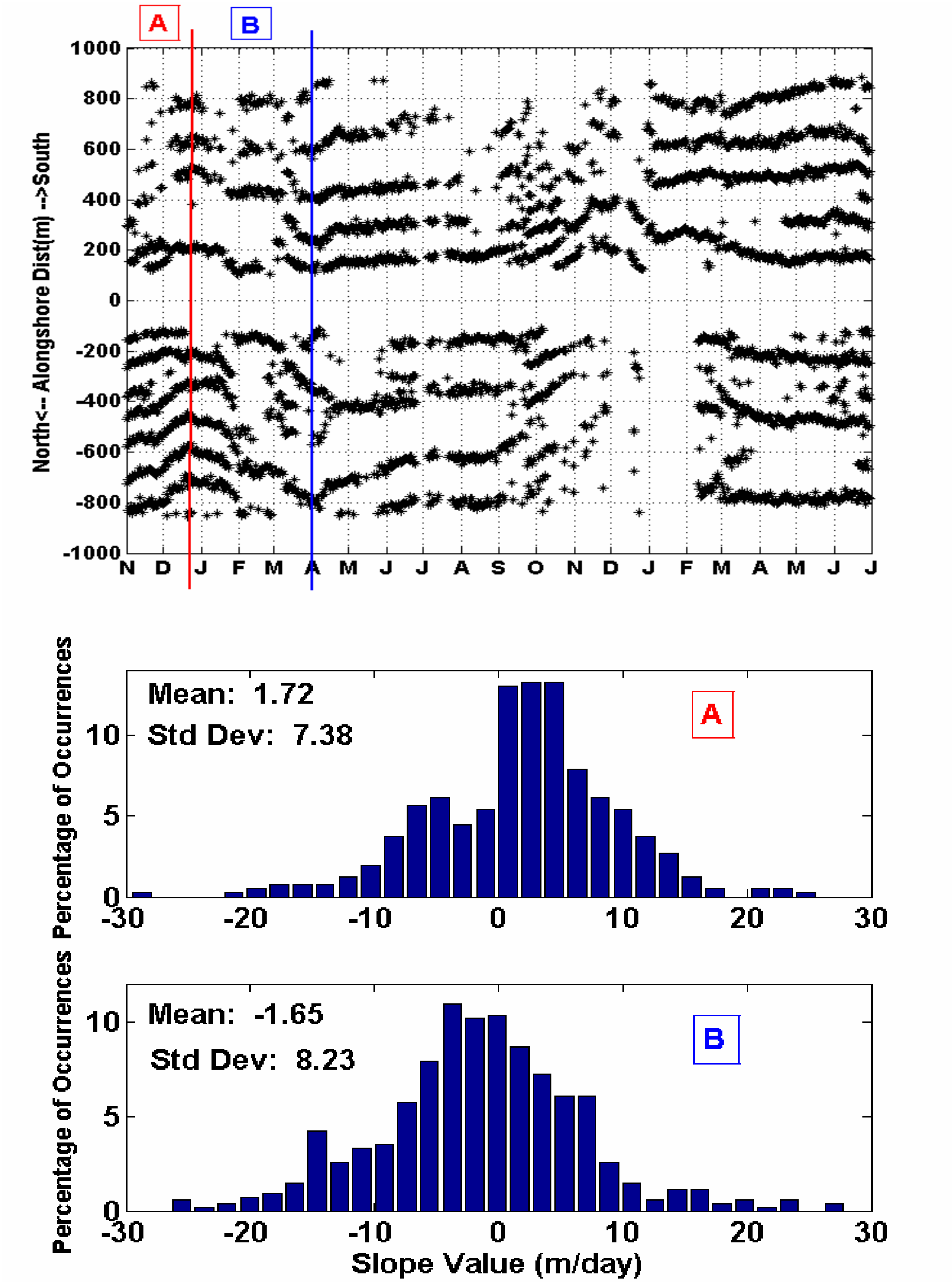

Figure 11. The location of the rip channels at Stillwell Hall, Fort Ord, from November 1, 2004, through December 20, 2004, and from December 21, 2004, through March 31, 2005, are shown in Sections A and B, respectively (top panel). Histograms of the rip channel migration rates calculated for Sections A and B (middle and bottom panels).

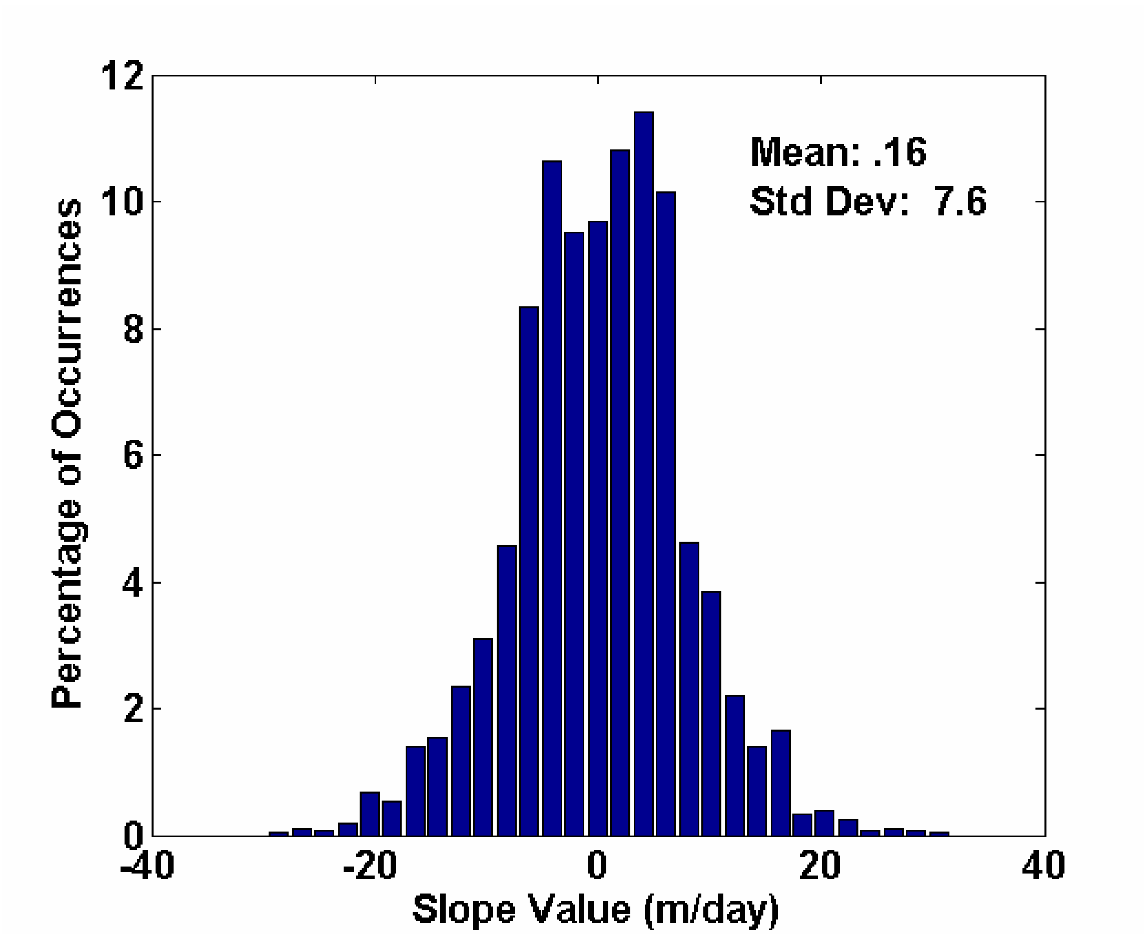

Figure 12. Histogram of the rip channel migration rates calculated at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006.

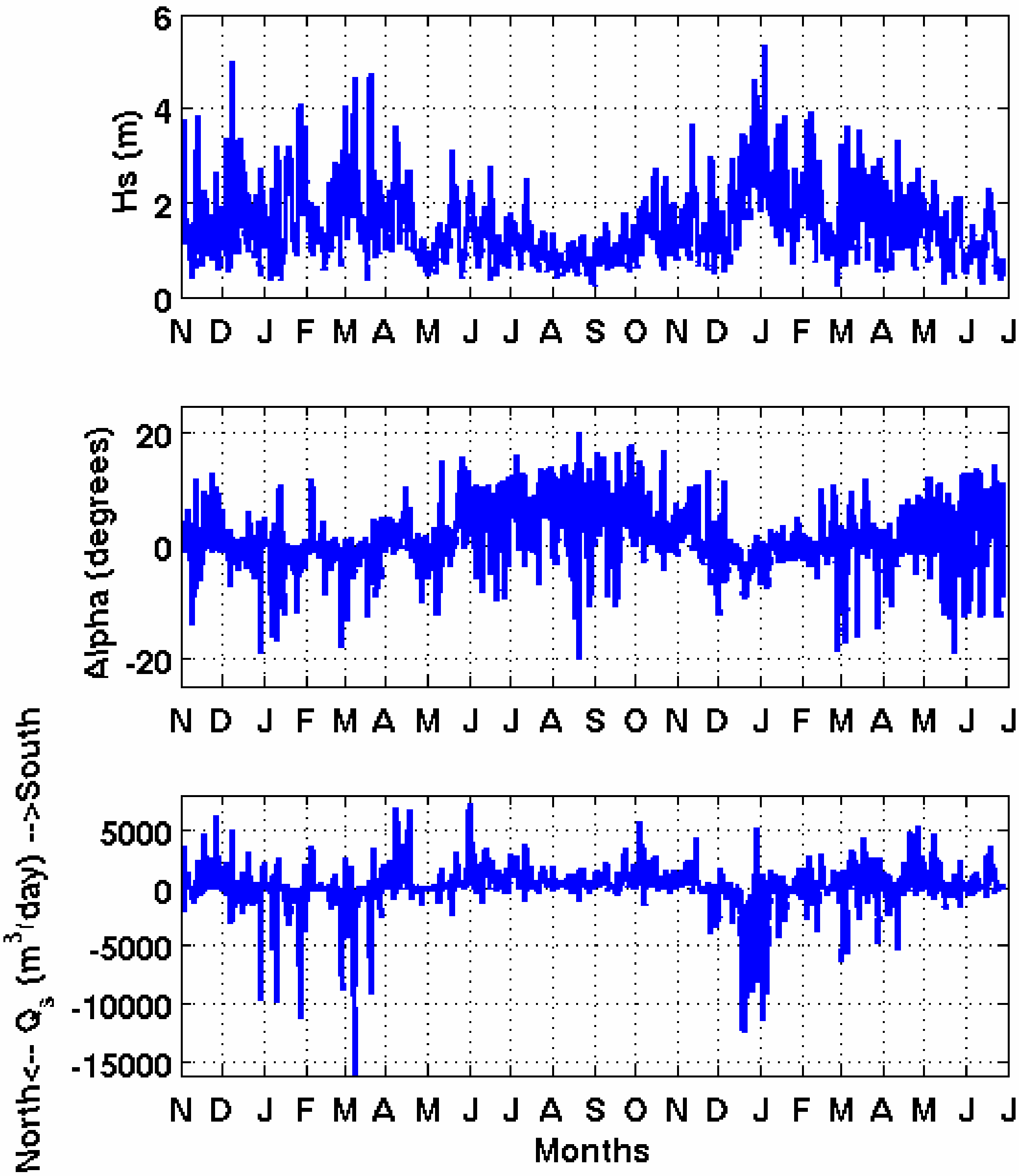

Figure 13. Significant wave height (top panel) generated from CDIP's refraction model at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006. Mean direction or alpha values (middle panel) calculated using the Fourier directional coefficients provided by Bill O'Reilly. The sediment transport rate (bottom panel) was calculated using the significant wave height and alpha values.

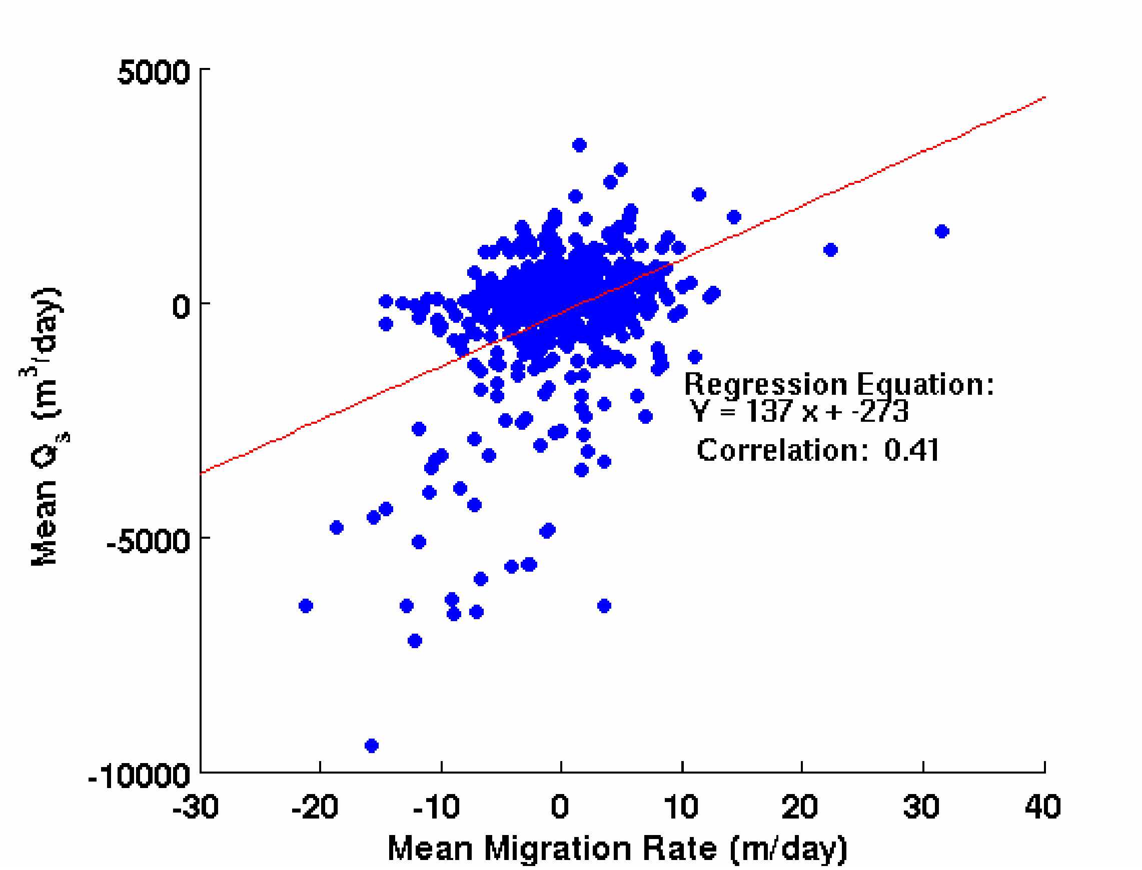

Figure 14. Linear regression of alongshore sediment transport rate and migration rate at Stillwell Hall, Fort Ord, from November 1, 2004, through June 30, 2006, using the original measured chart angle.

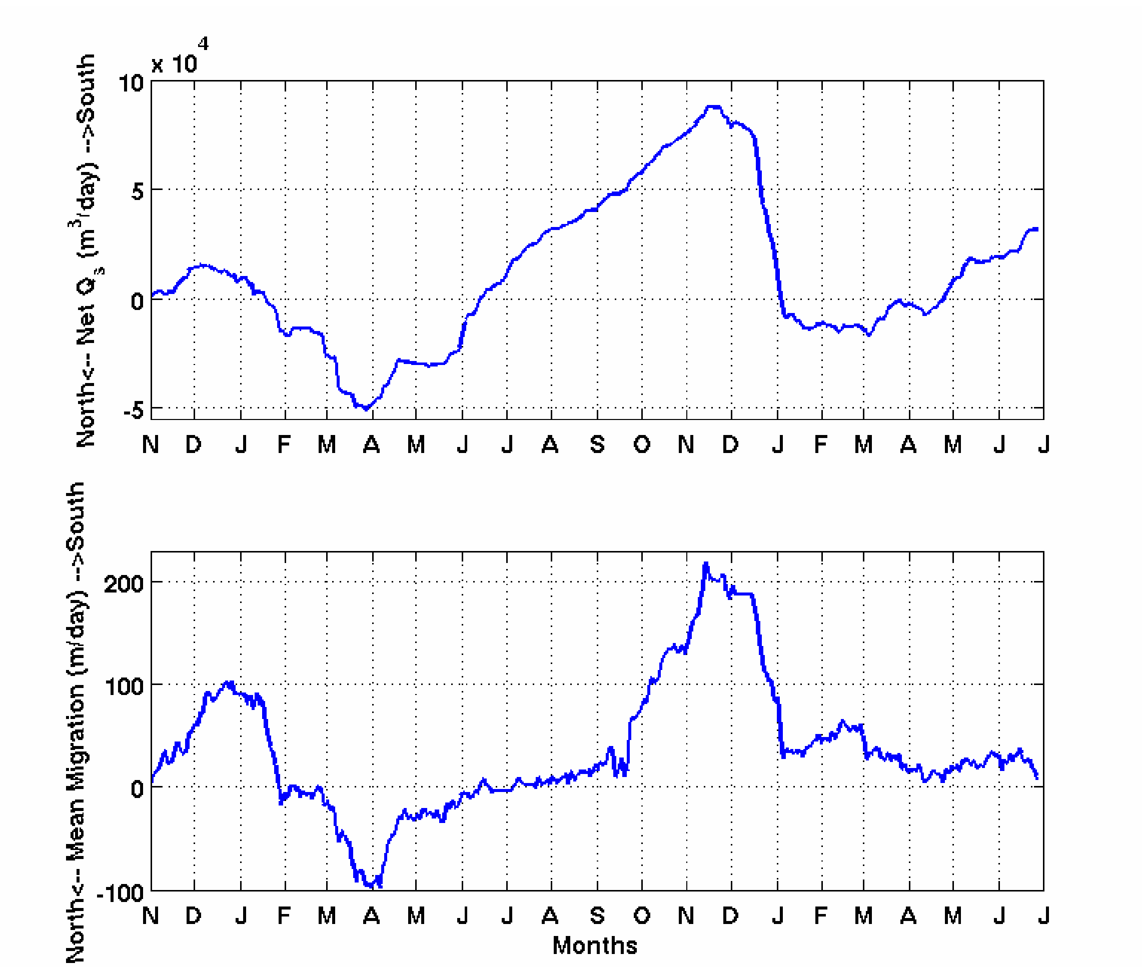

Figure 15. Net alongshore sediment transport rate (top panel) and mean migration (bottom panel) for Stillwell Hall, Fort Ord, from November 1, 2004 through June 30, 2006.

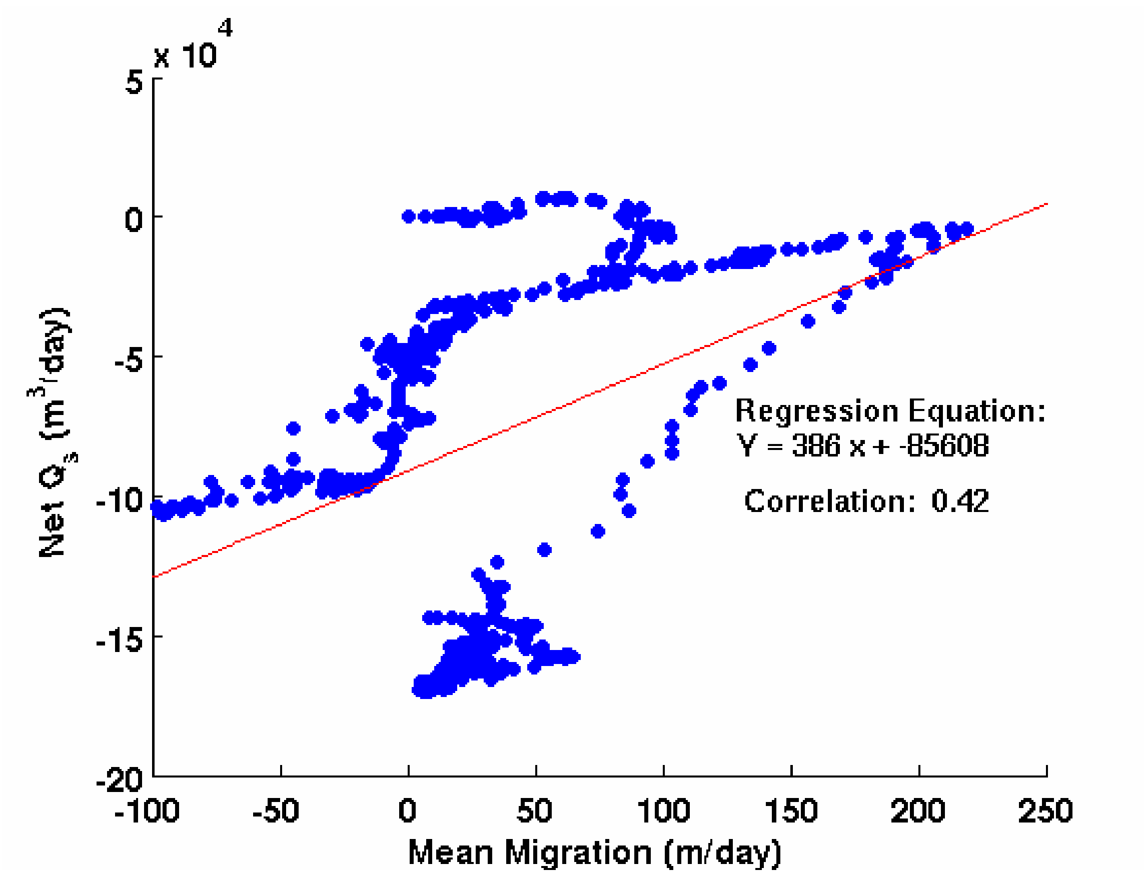

Figure 16. Linear regression of the net alongshore sediment transport and mean migration at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006, using the original measured chart angle.

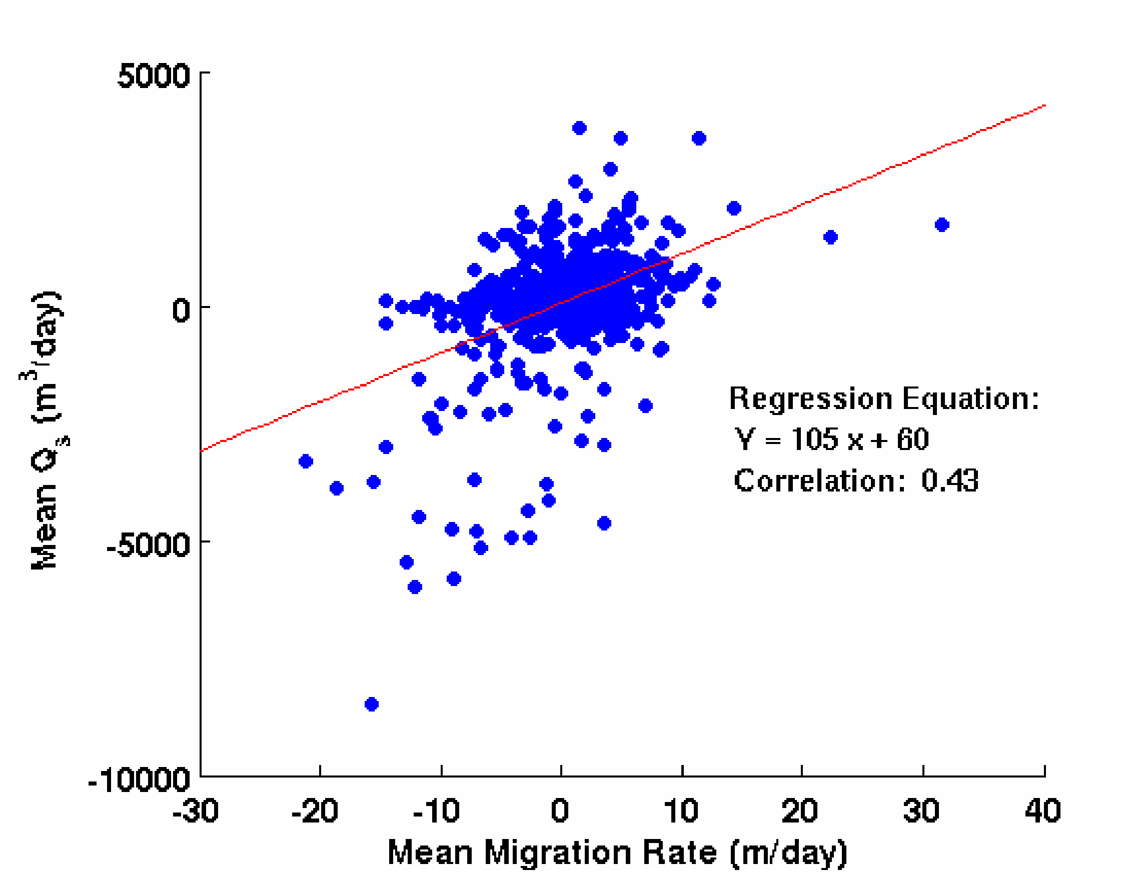

Figure 17. Linear regression of the alongshore sediment transport rate and mean migration rate at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006, using the southerly rotated angle.

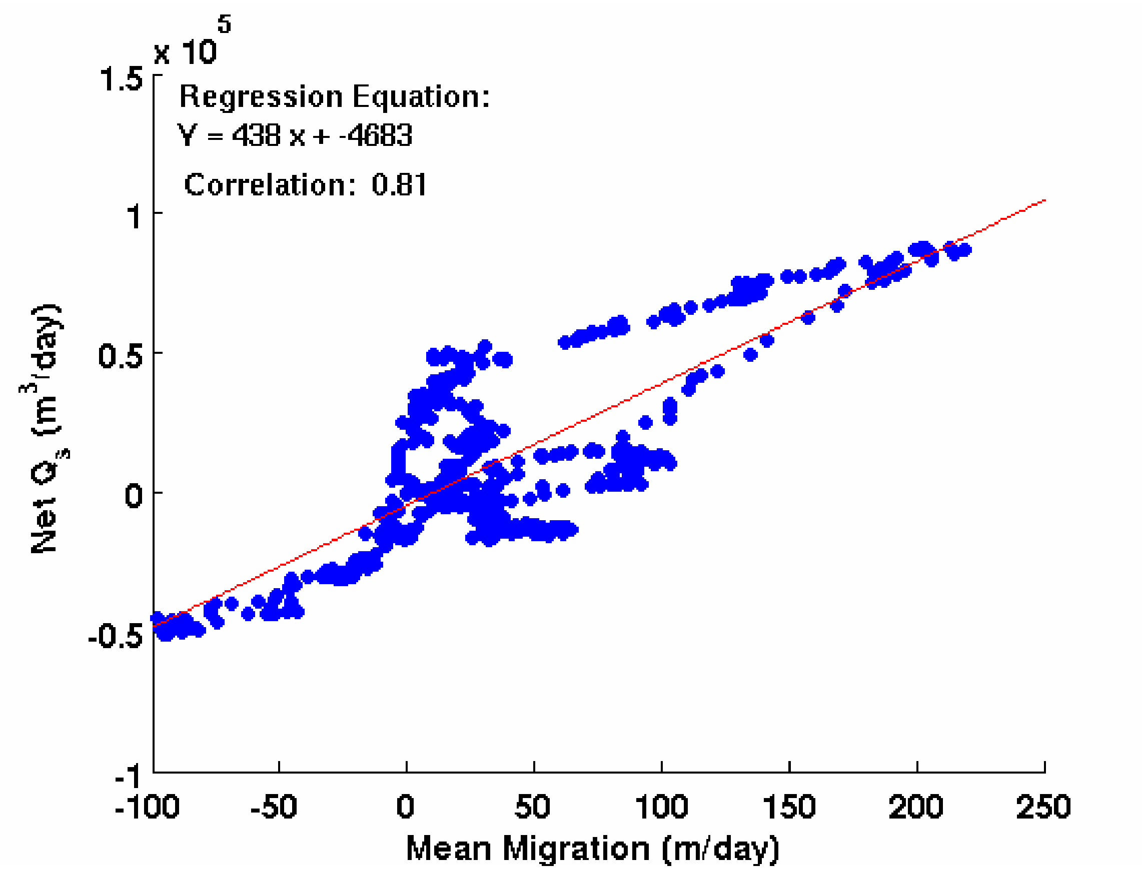

Figure 18. Linear regression of the net alongshore sediment transport and mean migration at Stillwell Hall, Fort Ord, for November 1, 2004, through June 30, 2006, using the southerly rotated angle.

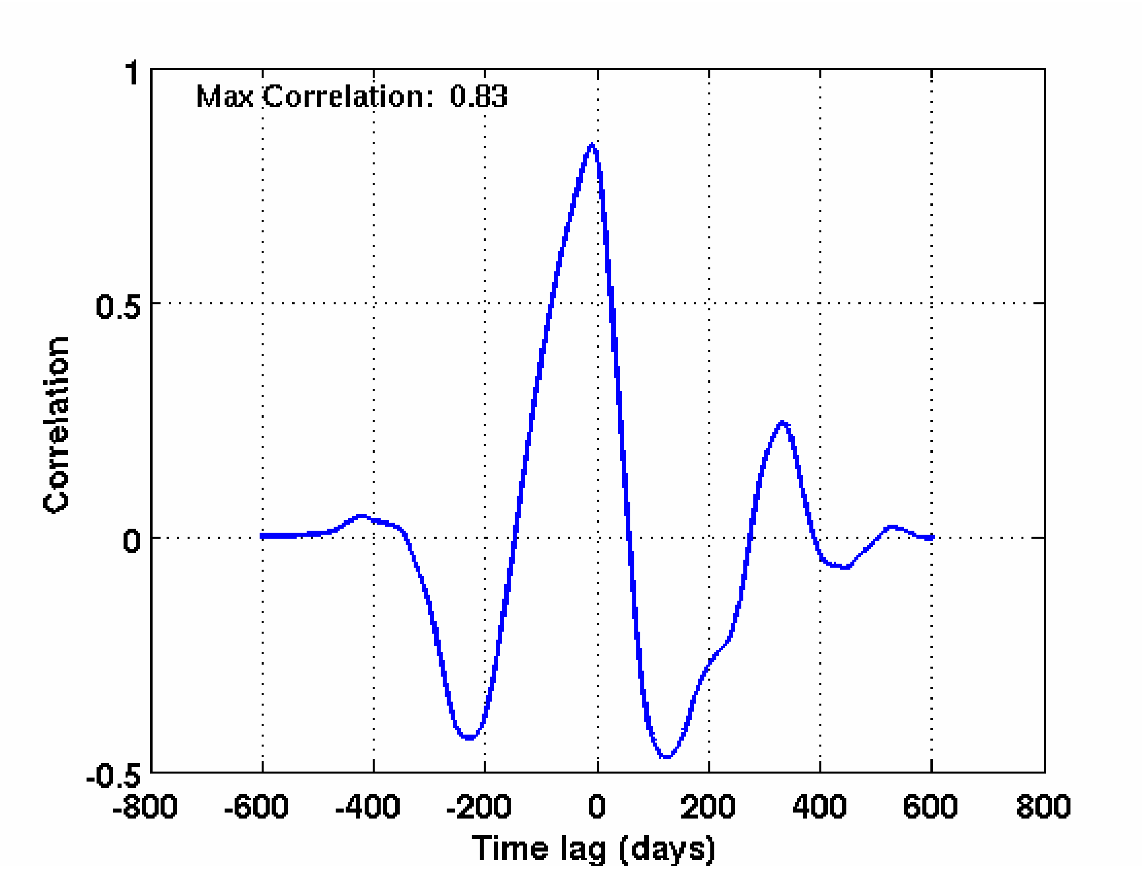

Figure 19. Cross-correlation of the mean migration and net alongshore sediment transport for Stillwell Hall, Fort Ord, from November 1, 2004, to June 30, 2006.

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